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Efficiency optimization of single phase motor using GA approach

***Abstract**. In this paper Genetic Algorithm for efficiency optimization of single phase shaded pole induction motor is implemented. For this purpose an extensive mathematical model of the motor is developed. The efficiency of the motor as an objective function of the optimization is selected. The optimization process is performed for different set of optimization parameters (three, four and five variables). The prototype as well as the optimized motor models afterwards are modeled and analyzed using Finite Element Method. An analysis of the magnetic field distribution, as well as flux density values, in the whole cross-sectional area of all models has been performed in order to validate the improvements of the optimized models in relation to the basic motor model.*

***Streszczenie.** W artykule przedstawiono zastosowanie algorytmu genetycznego do optymalizacji sprawności jednofazowego silnika indukcyjnego z utajonymi biegunami. W tym celu analizie poddano rozbudowany model matematyczny silnika. Funkcją celu w procesie optymalizacyjnym jest sprawność silnika. Proces ten jest przeprowadzany dla różnych układów parametrów optymalizacyjnych (trzy, cztery i pięć zmiennych). Prototyp oraz modele zoptymalizowanego silnika zostały poddane analizie metodą elementów skończonych. Została przeprowadzona analiza rozkładu pola magnetycznego , jak też wartości indukcji magnetycznej w pełnym przekroju wszystkich modeli w celu potwierdzenia poprawy modeli zoptymalizowanych w stosunku do modelu wyjściowego. (**Optymalizacja sprawności jednofazowego silnika przy użyciu algorytmu genetycznego**).*

Keywords: motor efficiency, optimization, finite element method, single phase shaded pole induction motor
Słowa kluczowe: sprawność silnika, optymalizacja, metoda elementów skończonych, jednofazowy silnik indukcyjny z utajonymi biegunami

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Introduction

Induction motors are widely used in industry because they are rugged inexpensive and maintenance free. It is estimated that more than 50 % of the world generated electric energy is consumed by electrical machines. Improving efficiency in electrical motors is important from economical point of view, as well as from the point of reduction of environmental pollution [1]. Single phase shaded pole motor belongs to the most widespread single phase motors, due to robust and reliable construction and low production costs, although its operational characteristics are not its strong side. Here are some common values for this type of motor: efficiency η (0.25÷0.4) and power factor $\cos\varphi$ (0.4÷0.6). Very important feature about this type of single phase motor is that the locked rotor current has a very close value to rated current meaning that motor is capable of sustaining overload or full load at locked rotor position which makes it irreplaceable driving force, especially in applications where a large starting torque is not required. In this paper the authors propose a methodology for improving the efficiency of this type of motor using Genetic Algorithm (GA) as an optimization tool in the optimal design of AKO-16 motor (Fig.1) product of MicronTech Company. Firstly, an analytical model of the motor is developed based on the revolving field theory and current symmetrical components. The analytical model accuracy is verified using experimental and manufacturer test data.

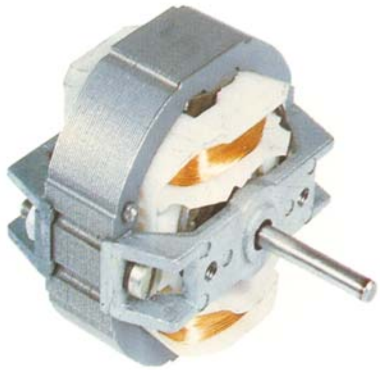
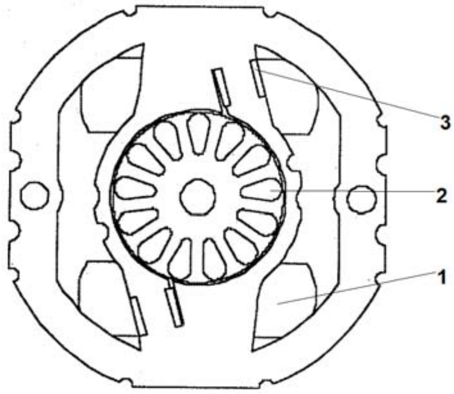


Fig.1. Motor physical layout

After the GA optimization the basic motor model (BM) is improved with three motor models using different number of optimization parameters. The first motor model is optimized with three variables (M1), the second (M2) and third motor (M3) model are optimized with four and five variables, respectively. The aim of the GA optimization is to maximize the efficiency of the motor, which is the objective function of the optimization. The evaluation of all motor models is done using the Finite Element Method (FEM) analysis.



1–main stator winding, **2**–squirrel cage winding, **3**–short circuit coil

Fig.2. Motor cross-section

GA method results

Genetic Algorithm has proved itself during recent years as a reliable, robust optimization technique that enables to obtain a global optimum of certain function by performing optimization search over many families of possible solutions thus avoiding location of one optimal solution which may not necessarily be the global optimum. Defining the input variables of the analytical motor model is the first step in the GA programming. The efficiency of the motor is chosen to be the objective function for optimization. Optimization is performed without changing motor outer dimensions which is important from mounting point of view. First motor model which is considered to be the basic motor model (BM) is derived from motor mathematical model of the prototype. All optimized motor models have different number of variables. The first motor model–M1 has three optimization parameters, the second model-M2 has four and the third motor model-M3 has five variable optimization parameters. In Table 1 the ranges of variation of the input variables for all motor models are presented, and in Table 2 their values after the optimization is done. Optimization is performed for rated operating point for motor slip s=0.16.

Table 1. Ranges of variation of GA parameters

	Variation range
Current density Δ (A/mm^2)	5 ÷ 10
Air gap flux density B_δ (T)	0.4 ÷ 0.45
Angle of rotor skew α_{sk} (°)	15 ÷ 20
Width of stator pole b_p (m)	b_p=0.012 ÷ 0.02
Shading portion of stator pole a (/)	a=0.2 ÷ 0.4

Table 2. Values of optimized parameters

M1 output	M2 output	M3 output
5.17	5.045	5
0.40035	0.40035	0.4
15.025	15.008	15.0035
0.016=const	0.016=const	0.012
0.25=const	0.2	0.2

The obtained parameters from the GA optimization afterwards are used for calculation of motor parameters and characteristics for all motor models. They are presented in Table 3 and Table 4. In Table 4 are presented motor parameters such as: current density-Δ, air gap flux density B_δ, angle f skew of rotor bars α_{sk}, diameter of copper wire in main stator winding-d_{cu}, number of turns in main stator winding-W, active and reactive resistance in main stator winding R_1 and X_1, in short circuit coil R_3 and X_3, in rotor winding R_2 and X_2, mutual reactance between stator windings X_{12} and between main stator winding and rotor X_{13}. All important motor operational characteristics are calculated for different slip s for the whole motor operating range (0÷1) for all motor models. Comparative characteristics of electromagnetic torque, input power and output power are presented in Figure 3, Figure 4 and Figure 5, respectively.

Table 3. Motor models characteristics

Quantity	BM	M1	M2	M3	Experim.	Producer
Stator current I_1 (A)	0.126	0.131	0.128	0.1235	0.129	0.11±10%
Rotor current I_2 (A)	0.0875	0.092	0.0941	0.09316	/	/
Short circuit coil I_3(A)	0.00643	0.00667	0.0046	0.0048	/	/
Power factor cosφ (/)	0.654	0.59224	0.6283	0.643	0.667	0.6376
Input power P_1 (W)	18.11	17.14	17.74	17.46	19.1	16±10%
Output power P_2 (W)	4.149	4.73	5.61	6	/	/
Torque M_{em} (mNm)	18.075	20.28	23.6	25.1	/	/
Efficiency factor η (/)	0.229	0.276	0.31	0.35	/	/

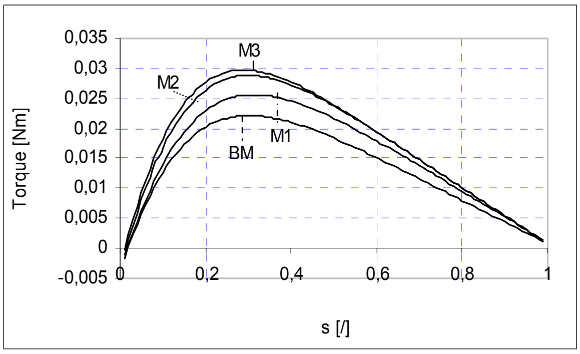


Fig.3. Electromagnetic torque characteristics

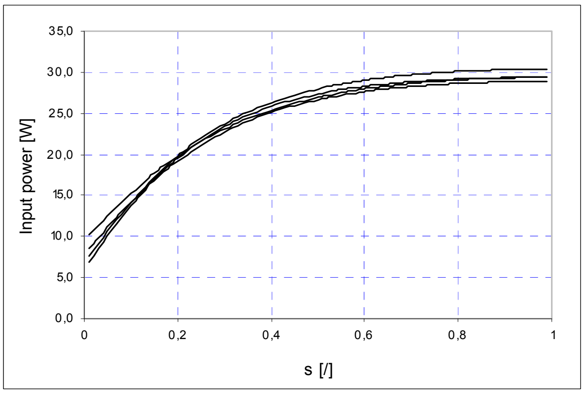


Fig.4. Input power characteristics

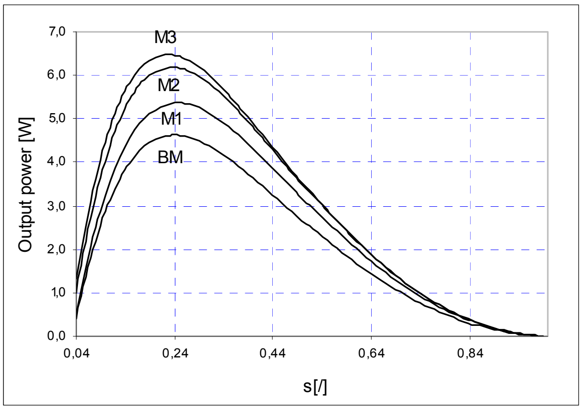


Fig.5. Output power characteristics

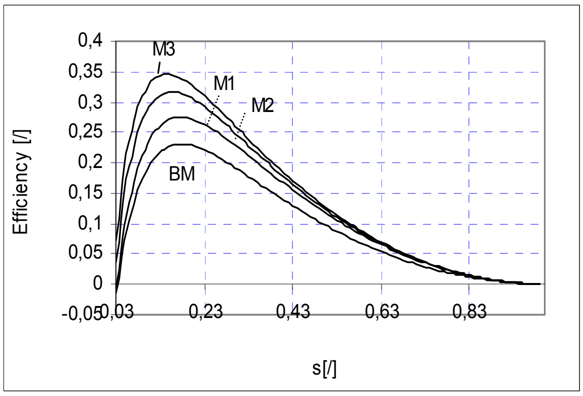


Fig.6. Efficiency characteristics

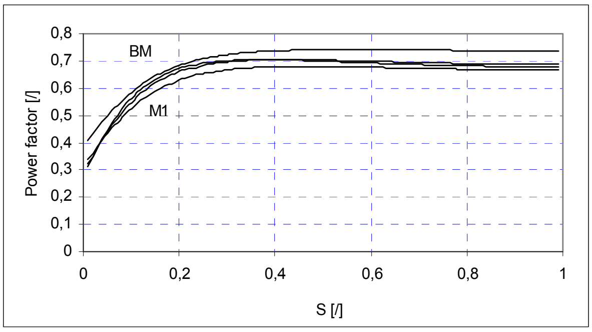


Fig.7. Power factor characteristics

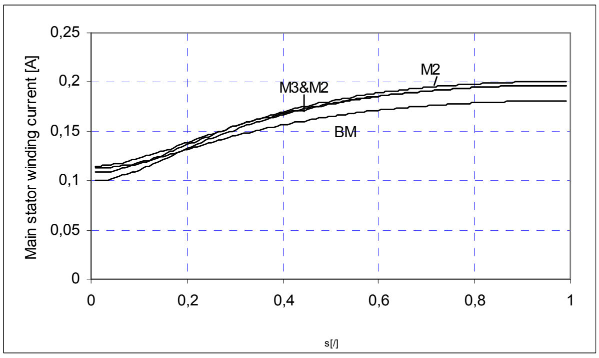


Fig.8. Characteristics of main stator winding current

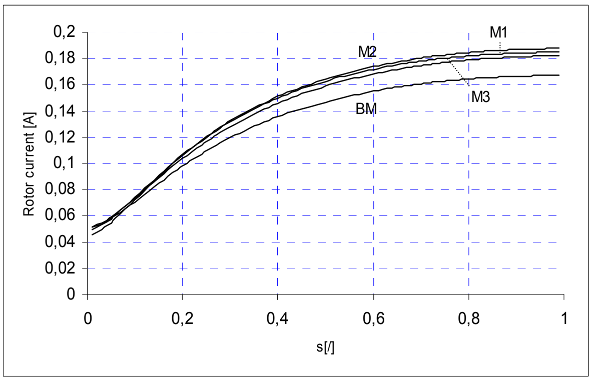


Fig.9. Characteristics of rotor winding current

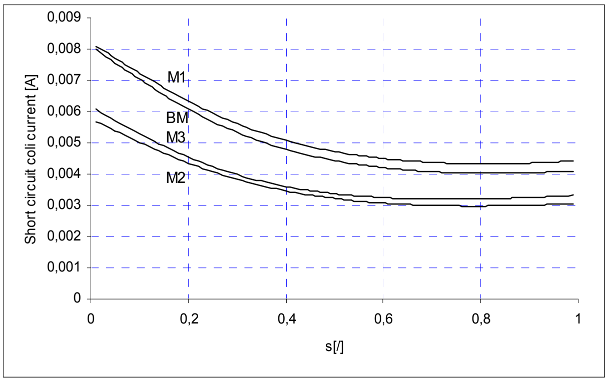


Fig.10. Characteristics of short circuit coil current

In Figures 6, 7 and 8 comparative characteristics of efficiency factor, power factor and main stator winding current for all motor models are presented, while in Figure 9 and Figure 10 comparative characteristics of rotor winding current and short circuit coil current are presented, respectively. Compared to authors previous work [2], in this case when the efficiency is adopted as objective function of the optimization, the increase of the efficiency is achieved by increasing the motor output power without increasing the motor power consumption, for the same value of the power factor for rated operational point which is important for the energy savings.

Table 4. Motor models characteristics

BM	M1	M2	M3
Δ=5 (A/m^2)	Δ=5.17 (A/m^2)	Δ=5.0 (A/m^2)	Δ=5 (A/m^2)
B_δ=0.404(T)	B_δ=0.40035(T)	B_δ=0.4003(T)	B_δ=0.4 (T)
α_{sk}=17 (^{0})	α_{sk}=15.0025(^{0})	α_{sk}=15.008(^{0})	α_{sk}=15.003 (^{0})
d=2,4(mm)	d=1,8(mm)	d=1.8(mm)	d=1.8(mm)
bp=0,016(m)	bp=0,016(m)	bp=0,016(m)	bp=0,012 (m)
a=0.25	a=0.25	a=0.2	a=0.2
d_{cu}=0.14(mm)	d_{cu}=0.18 (mm)	d_{cu}=0.18(mm)	d_{cu}=0.18 (mm)
W=3488 turns	W=3520 turns	W=3520 turns	W=3522 turns
R_1=492.98 Ω	R_1=330.5 Ω	R_1=341.89 Ω	R_1=341.95 Ω
X_1=498.17 Ω	X_1=515.83 Ω	X_1=462.68 Ω	X_1=449.13 Ω
R_2=497.04 Ω	R_2=458 Ω	R_2=457.93 Ω	R_2=458.54 Ω
X_2=76.71 Ω	X_2=78.12 Ω	X_2=89.3 Ω	X_2=99.47 Ω
R_3=18474 Ω	R_3=18814.8 Ω	R_3=28234.4Ω	R_3=27292.3 Ω
X_3=127.53 Ω	X_3=129.87 Ω	X_3=127.46 Ω	X_3=125.18 Ω
X_{12}=2163.3 Ω	X_{12}=2202.97Ω	X_{12}=2518.4 Ω	X_{12}=2804.87Ω
X_{13}=175.91 Ω	X_{13}=179.13 Ω	X_{13}=183.84 Ω	X_{13}=220.12 Ω

The small modifications in motor inner construction contributed in the increase of the motor output power, as well as improved motor efficiency. The increase of efficiency is followed by increase of electromagnetic torque which is also important from operational point of view. In Table 5 percentage increase of efficiency and electromagnetic torque in optimized motor models compared to the basic motor model is presented.

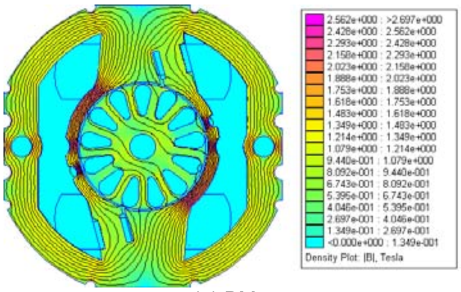
Table 5. Comparison of efficiency factor at different motor models

	BM	M1	M 2	M3
Electromagnetic torque M_{em} (Nm)	0.018	0.0202	0.0236	0.0251
Improvement of M_{em} (%)	-	12	31	39.4
Efficiency η (/)	0.229	0.276	0.31	0.35
Improvement of η (%)	-	20.5	35.3	52.8

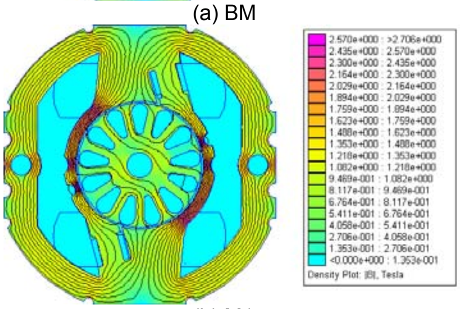
FE method results

Motor model is input in FE program for calculation of magnetic flux density in motor cross-section as well as in motor air gap for different operating regimes. Motor exact geometry is input, boundary condition are defined which in this case is a Dirichlet boundary condition. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define A = 0 along a boundary to keep magnetic flux from crossing the boundary. Materials in all motor regimes are defined including the non-linearity of magnetic material and magnetic core laminations [3]. Time harmonic analysis is run at frequency f=50 Hz. Current density in main stator winding is input while in short circuit coil and rotor cage currents are freely induced. Rotor bars conductivity is adjusted according to motor slip. All motor models are analyzed for different operating regimes. For that purpose appropriate current densities are inputted in main stator winding and rotor bars conductivity is modeled according to motor slip. Results of magnetic flux distribution at rated load for all motors are presented in Figure 11.

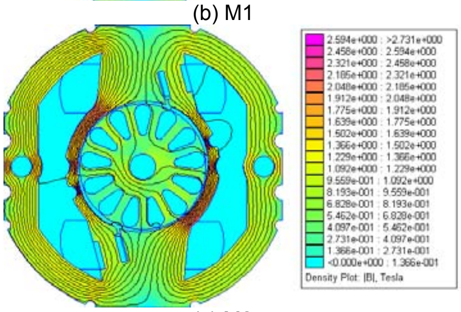
In Table 6 maximal and minimal values of magnetic vector potential A_{max} and A_{min} as well as maximal value of magnetic flux density in motor core cross-section B_{max}, flux per pole – Φ as well as flux linkage – F, for rated load operating conditions are presented.



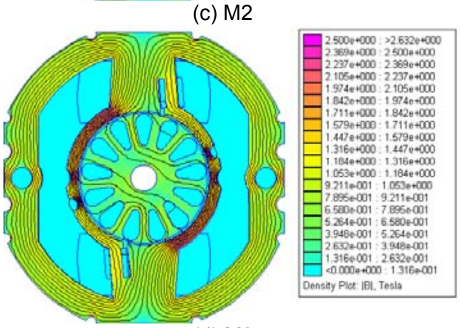
(a) BM



(b) M1



(c) M2

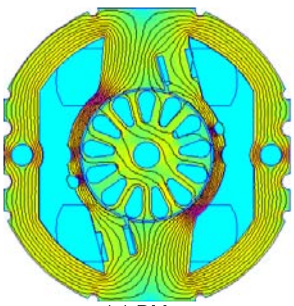


(d) M3

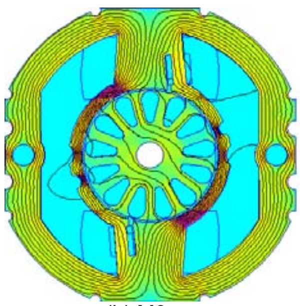
Fig.11. Magnetic flux density distribution at rated load

Table 6. Flux density and magnetic vector potential at rated load

Parameter	BM	M1	M2	M3
A_{max} (Vs/m)	5.1x10^{-3}	5.3x10^{-3}	5.4x10^{-3}	4.4x10^{-3}
A_{min}(Vs/m)	-5.1x10^{-3}	-5.3x10^{-3}	-3.7x10^{-3}	-4.4x10^{-3}
B_{max} (T)	2.594	2.57	2.594	2.5
Flux per pole (Vs)	0.98x10^{-4}	1.04x10^{-4}	0.88x10^{-4}	0.7x10^{-4}
Flux linkage (Vs)	0.343	0.366	0.309	0.25



(a) BM



(b) M3

Fig.12. Magnetic flux density distribution at rated load with soft magnetic material in stator's bridge

Soft magnetic material is implemented only in construction of stator's bridge, in order to improve magnetic flux density distribution in motor cross-section. The obtained results for motor models BM and M3 at rated load operating condition are presented in Figure 12. From the presented results it can be concluded that magnetic flux density in stator's bridge for both motor models is considerably lowered and with this action the high saturation of magnetic material in this critical part of motor is avoided.

Conclusion

Single phase shaded pole motor belongs to a group of small motors well-know for its robust construction and reliability, but also known as motor with relatively poor efficiency and power factor. For that reason an optimization procedure was performed using genetic algorithms as a tool. The efficiency of the motor was defined as an objective function for the optimization. The optimization model is developed based on method of symmetrical components with gradual increase of number of varied parameters from three up to five. The results form the optimization procedure have proved gradual increase of the efficiency of the motor of 20.5% in the first optimized model, 35.3% in the second model and up to 52.8% in the last optimized model which utilizes five input variable parameters. The increase of the efficiency is followed by increase of electromagnetic torque of 12% in the first model, 31% in the second and 39.4% in the third optimized motor model. The increase of the efficiency is obtained without increasing the motor input power, that is 18 W in all motor models, which is important from the aspect of power consummation, but at the same time output power is considerably increased from 4.2 W in the basic model up to 6 W in the third optimized motor model. Magnetic flux density in the motor cross-section is calculated and presented using Finite Element Method. Different operating regimes were investigated and in the paper is presented rated load operating regime. By using the FE method it was concluded that the stator bridge is experiencing high values of magnetic flux density and magnetic material saturation in the basic, as well as in optimized motor models. Therefore, soft magnetic material is placed in the construction of the stator bridge which considerably lowered the magnetic flux density in this saturated part of the motor construction regarding high values of flux densities.

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